PASTA Project: Data Analysis

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INTRODUCTION

The aim of the PASTA project (Production with Accelerator of Sc-47 for Theranostic Applications), developed in the framework of LARAMED (LAboratory of RAdionuclides for MEDicine) [1] at INFN-LNL and funded by CSN5 with the *Bando Giovani Ricercatrici e Ricercatori N. 18203* (2017-2018), is the measurement of nuclear cross sections for the production of ^{47}Sc. Scandium-47, thanks to its β^- and γ-radiation (Table 1) [2], is one of the new radionuclides that are intrinsically suitable both for therapeutic and diagnostic purposes.

Table 1. Decay characteristics of ^{47}Sc [2]

^{47}Sc	Imaging emission	Therapy emission	
	γ	β^-	β^-
Half-life	159.381 keV 15	440.9 keV 19	600.3 keV 19
3.3492 d 6	(68.3% 4)	(68.4 % 6)	(31.6 % 6)
		Mean β- energy:162.0 keV	

The worldwide increasing interest in the development of personalized treatments is well-represented by the recent Coordinated Research Project (CRP), promoted by the International Atomic Energy Agency (IAEA), focused on the study of "*^{67}Cu, ^{186}Re and ^{47}Sc as Emerging Theranostic Radionuclides*" [3].

The main advantage of ^{47}Sc-labelled compounds, and theranostic radionuclides, is the possibility to perform low-dose imaging studies prior therapy with the same radiopharmaceutical, allowing the selection of patients with a significant chance of responding to the specific treatment. The critical issue in the use of ^{47}Sc is its lack of availability in enough quantities and at a reasonable cost.

The PASTA project aims to answer to the increasing request of ^{47}Sc production for clinical applications by exploiting proton beams up to 70 MeV. This goal can be achieved: a) by measuring the cross section of the most promising proton-induced nuclear reactions (^{nat}V(p,x)^{47}Sc and ^{48,49,50}Ti(p,x)^{47}Sc); b) optimizing the irradiation parameters considering the co-production of contaminant radionuclides (such as ^{46}Sc, half-life 83.79 d); c) studying a radiochemical procedure to extract ^{47}Sc from the irradiated target. This work describes the research activities performed during this project and the data analysis procedure used to calculate the cross sections to produce ^{47}Sc and ^{46}Sc by using ^{nat}V targets. Same data analysis has been applied to estimate the cross section of all co-produced radionuclides: ^{44}Sc, ^{44m}Sc, ^{43}Sc, ^{48}Sc, ^{48}V, ^{43}K, ^{42}K, ^{48}Cr, ^{49}Cr, ^{51}Cr.

METHODS

Since the beam line devoted to cross section measurements in the framework of LARAMED project is still under development, all irradiation runs for the PASTA project (Table 2) have been carried out at the Arronax facility (Nantes, France) [4], where a dual-extraction multi-source cyclotron is installed, and 70 MeV proton beam are available. A dedicated target-holder, collimator in graphite and related plastic support have been realized at INFN-LNL and subsequently installed in the Arronax beam-line and used for the irradiations runs of the PASTA project (Fig. 1).

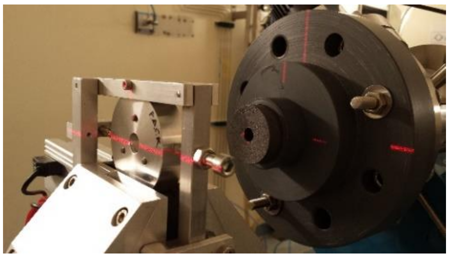

Figure 1: Photograph of the alignment procedure of target-holder and collimator on the beam-line

During the experiments, the stacked-foils technique has been used in order to obtain at each irradiation run several cross section measurements at different energies. Irradiation parameters are reported in Table 2. The thin target foils (thickness up to 20 µm) have been separated by thick aluminum foils used as beam energy degrader. In order to measure the proton beam current, monitor foils have been used and the cross sections recommended by IAEA [5] have been taken into account for the data analysis, in particular the ^{nat}Ni(p,x)^{57}Ni and ^{27}Al(p,x)^{24}Na reference nuclear reactions.

Table 2. Main characteristics of the 6 irradiations performed

n	Reaction	N° target foils	Proton Energy (MeV)	Duration (minutes)	Proton Current (nA)
1	^{nat}V(p,x)^{47}Sc	3	70	90	≈ 105
2	^{nat}V(p,x)^{47}Sc	3	54	90	≈ 100
3	^{nat}V(p,x)^{47}Sc	3	61	90	≈ 100
4	^{48}Ti(p,x)^{47}Sc ^{nat}V(p,x)^{47}Sc	2 3	34	90	≈ 120
5	^{48}Ti(p,x)^{47}Sc ^{nat}V(p,x)^{47}Sc	4 1	40	50	≈ 130
6	^{48}Ti(p,x)^{47}Sc ^{nat}V(p,x)^{47}Sc	3 1	34	90	≈ 103

RESULTS

After irradiation, γ-spectrometry measurements have been carried out for each foil with a HPGe detector calibrated for solid targets. All the produced radionuclides have been considered, i.e. ^{47}Sc, ^{46}Sc, ^{44}Sc, ^{44m}Sc, ^{43}Sc, ^{48}Sc, ^{48}V, ^{43}K, ^{42}K, ^{48}Cr, ^{49}Cr, ^{51}Cr, by using the decay data available in [2].

Data analysis has been performed by following the recent paper published by Otuka et al. (2017) [6]. The cross section σ of the radionuclides of interest x has been calculated considering the reference radioisotope r produced in the monitor foil and using the following formula:

$$\sigma_x = \sigma_r \frac{c_x}{c_r} \frac{n_r}{n_x} \frac{\varepsilon_r}{\varepsilon_x} \frac{I_r}{I_x} \frac{f_r}{f_x}$$

where σ_r is the reference cross section (available on the IAEA website [5]), C is the net number of counts of the γ-line considered, n is the number of target atoms/cm^2, ε is the detector efficiency at the energy of the γ-line considered, I is the intensity of the γ-line and f is the following decay correction factor:

$$f_x = \left(1 - e^{-\lambda_x t_i}\right) e^{-\lambda_x t_{c,x}} \left(1 - e^{-\lambda_x t_{m,x}}\right)/\lambda$$

The correction for the irradiation time t_i, the cooling time t_c from the End Of Bombardment (EOB) to the γ-spectrometry and the measuring time t_m has been considered.

In order to follow the decay of the radionuclides of interest all experiments have been designed to allow several γ-spectrometry measurements of each sample at different times after the EOB. At least No. 5 spectra for each target foil have been acquired. In order to evaluate the activity of the long-lived ^{46}Sc isotope (83.79 d half-life), all the target foils of each irradiation run have been measured again during the following run.

This procedure allows to have several cross section estimations for each sample. The associated error has been calculated by following the paper published by Otuka et al. (2017) [6] and statistical and systematic uncertainties has been taken into account. The cross section value associated with each foil is the weighted average of the single values obtained with an associated error, and thus it is smaller than that of a single measurement.

As an example, we report hereafter the results obtained from 6 different γ-spectra for the ^{nat}V foil irradiated in the second run and arranged in the first position of the stacked-foil (named *V21*). Figure 2 reports the results obtained for ^{47}Sc and ^{46}Sc radionuclides for the *V21* foil. These graphs show the six cross section obtained for each acquired spectrum (black dots) and the single value obtained by weighted average (black triangle). For both the elements considered it is possible to note the reduction of the uncertainty associated with the cross section.

This procedure has been applied to each irradiated foil. An additional advantage of the described data analysis is the possibility to verify potential discrepancies at specific γ-lines due to possible interferences between two different elements.

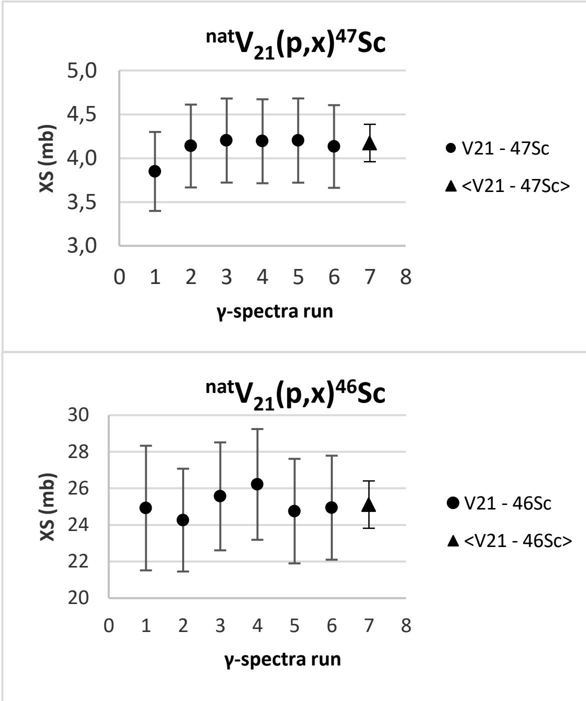

Figure 2: Production cross section of $^{47,46}Sc$ for six different spectra (black dots) and corresponding weighted average (black triangle) for the V21 foil

CONCLUSIONS

This work reports the data analysis carried out during the PASTA project, focused on the accelerator-based production of ^{47}Sc by using proton-beams. Six irradiation runs have been performed at the Arronax facility by using ^{nat}V foils arranged in stacked-foil target. Data analysis has been completed and results will be published soon.

ACKNOWLEDGMENTS

Authors would like to thank colleagues at INFN-LNL supporting this research activity and the staff at the Arronax facility where the irradiation runs were performed. This work is carried out in the context of the CRP by IAEA [3].

[1] Esposito J et al., LARAMED: A Laboratory for Radioisotopes of Medical Interest, Molecules 2019, 24, 20

[2] NuDat database 2.6, http://www.nndc.bnl.gov/

[3] IAEA Coordinated Research Project (CRP), *Therapeutic Radiopharmaceuticals Labelled with New Emerging Radionuclides (^{67}Cu, ^{186}Re, ^{47}Sc)*, http://cra.iaea.org/cra/explore-crps/all-active-by-programme.html

[4] F. Haddad, Eur.J.Nucl.Med.Mol.Imaging (2008) 35:1377-87

[5] Monitor Reactions 2017, https://www-nds.iaea.org/medical/monitor_reactions.html

[6] N. Otuka et al., Uncertainty propagation in activation cross section measurements, Radiation Physics and Chemistry 140 (2017) 502-510